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IDENTIFICATION OF EUROPEAN AIR MASSES USING AN INTERACTIVE COMPUTER TECHNIQUE FOR SEPARATING MIXED NORMAL DISTRIBUTIONS

by

CRANSTON R. COLEMAN, JR.

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

DEPARTMENT OF MARINE, EARTH, AND ATMOSPHERIC SCIENCES

RALEIGH

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APPROVED BY:

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ABSTRACT

COLEMAN, CRANSTON R., JR. Identification of European Air Masses Using an Interactive Computer Technique for Separating Mixed Normal Distributions. (Under the direction of DR. DAVID A. BARBER, DR. JERRY M. DAVIS, and DR. ALLEN J. RIORDAN.)

The interactive computer program developed here is a time and work saving extension of a partial collective method for examining air masses which was first introduced by Essenwanger (1954). The partial collective method is based on the assumption that frequency curves of conservative air mass properties, such as equivalent potential temperature, are comprised of a series of normal curves, each representing a different air mass.

For the purposes of this study, the interactive computer method is applied to the analysis of fall and winter air masses over six European stations with examination of equivalent potential temperature at the surface, 850mb, 700mb, and 500mb levels. Five major air masses are identified as affecting central Europe during the winter at the surface, 850mb and 700mb levels, and four air masses at the 500mb level. In the fall, six air masses are discernable at the surface and 700mb with five appearing at 850mb and 500mb.

The computer technique which is used here to analyze European air masses is not limited to air mass analysis, but may be applied universally to the separation of mixed normal distributions.

BIOGRAPHY

Captain Cranston Riley Coleman, Jr., was born at Fort Bragg, North Carolina on February 22, 1949. He spent his early childhood in Japan and Germany as a military dependent. He was graduated from White Station High School in Memphis, Tennessee in 1966. He entered Memphis State University and received a Bachelor of Science degree in Mathematics in May 1971.

The author was commissioned into the US Air Force and was assigned to the Air Training Command Basic Meteorology Program at the University of Texas at Austin from July, 1971 to May, 1972. During the next seven years, Captain Coleman served as an Air Force weather officer at Kelly AFB, TX; Randolph AFB, TX; Fort Bragg, NC; and Camp Casey, Korea. While at Camp Casey, he taught meteorology and physics at the Los Angeles Community College on-post campus.

In June 1979, Captain Coleman was assigned to the US Air Force Institute of Technology Civilian Institutions Program for graduate study in meteorology and mathematics at North Carolina State University. He is currently working as an operations research analyst at HQ Air Weather Service, Scott AFB, Illinois.

The author is married to the former Sandra Lynn DeLozier. Mrs. Coleman was graduated magna cum laude from Memphis State University in May 1971 with a Bachelor of Science Degree in Mathematics.

ACKNOWLEDGEMENTS

The author wishes to express his deepest appreciation to the many people who have inspired, advised, and assisted in the preparation of this study. In particular, he would like to thank the members of his Advisory Committee Dr. D. A. Barber, Dr. J. M. Davis, and Dr. A. J. Riordan, who guided his efforts, and his wife Sandy, whose assistance in the preparation of the manuscript and moral support throughout the study were invaluable.

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INTRODUCTION

Scientists at the U.S. Army Atmospheric Sciences Lab are currently developing computer simulation models for the electro-optical environment in Europe. These models are designed to test the effectiveness of electro-optical weapons guidance systems which are dependent on atmospheric extinction coefficients.

Recent efforts by Nilsson, Duncan, and Lindberg directly correlate aerosol extinction coefficients with air mass types. Nilsson (1979) classifies dry-particle size distributions according to air mass type and then uses a growth factor to predict the particle size distribution for a given relative humidity. These distributions are then related to atmospheric extinction. Duncan and Lindberg (1981) found that they could predict infrared extinction coefficients when given the visibility if they first separated their data by air mass type. Both of these studies indicate that droplet size distributions have different characteristic values for different air mass types.

In order to incorporate this information into the electro-optical simulation models realistically, the Atmospheric Sciences Lab researchers have stated that they must have a practical method for determining how often different air mass types occur in Europe, Kays (1982). This study was undertaken to provide such a method.

HISTORICAL PERSPECTIVE & LITERATURE REVIEW

The original theory for the classification of air mass types as an aid to the synoptic meteorologist was developed by the Norwegian school of meteorologists, notably Bjerknes and Bergeron (1928). Their ideas were built on the observed formation of large horizontally homogeneous air masses over various source regions. These source regions are extensive areas of uniform surface properties over which air tends to remain long enough for the vertical distribution of temperature and moisture to approach equilibrium. Once in a state of approximate equilibrium, very little change occurs in the temperature and moisture distributions as long as the air masses remain over their source regions. Eventually, changes in the hemispherical wave patterns of the general circulation force the air masses out of their source regions. This movement causes the air mass temperature and moisture profiles to be modified. The nature and rate of modification depends on the surface characteristics over which the air masses move. Thus, a cool, dry air mass which develops over a northern continental source region and moves south over a warm body of water will be heated from below and absorb moisture through evaporation from the surface.

These considerations led naturally to an air mass classification scheme which is based on the latitude of the source region and its surface characteristics. Northern source regions are called "polar" and southern regions "tropical." The terms "continental" or "maritime" describe the surface characteristics. Bergeron's classification also notes air masses as being either colder or warmer than the underlying surface, thus providing an indication of the stability of the lower layers. The air masses which could be defined under this system are listed in Table 1.

TABLE 1. AIR MASSES CLASSIFIED ACCORDING TO SOURCE REGION AND RELATIVE TEMPERATURE

Symbol	Name	Symbol	Name
mPk	Maritime Polar (cold)	mPw	Maritime Polar (warm)
cPk	Continental Polar (cold)	cPw	Continental Polar (warm)
mTk	Maritime Tropical (cold)	mTw	Maritime Tropical (warm)
cTk	Continental Tropical (cold)	cTw	Continental Tropical (warm)

Bergeron further refined the latitudinal categories in 1928 by recognizing the existence of three fronts separating four air masses. These are the Arctic front between Arctic and polar air, the polar front between polar and tropical air, and the intertropic front separating tropical and equatorial air. "Arctic" and "equatorial" were thus added to "polar" and "tropical" as air mass latitudinal classifications.

Willett (1933) felt that Bergeron's classification scheme was inadequate because it gave no indication of the modifications taking place as an air mass moves away from its source region. Instead of using generalized source region types, Willett developed an absolute system for North

America which designated air masses as being from specific sources (Table 2). For example, in classifying a maritime surface, he refers to the Pacific, Atlantic, or Gulf of Mexico using the general term "maritime" only when the exact origin is undetermined or when air from one source region is mixed with another. Willett also added the upper levels of the semipermanent highs in the southern part of the westerlies to his list of source regions. Air masses from this source region are called tropical superior air masses and are characterized by subsidence, high temperatures and low humidities. Tropical superior air is normally found over the southern U.S. at mid and upper levels and over the central U.S. at somewhat higher levels. Willett designed his classification system for indigenous meteorologists familiar with local source regions.

There are merits to both Bergeron's generic scheme and Willett's absolute classification system. This led Showalter (1939) to compare the two systems. He rejected Willett's scheme in favor of Bergeron's, pointing out that Willett's system lacks a means of identifying stability. While both systems gave forecasters an idea of the vertical profiles over data sparse areas, it was Bergeron's basic system which regional meteorologists chose to expand as they sought to be more exact in describing the air masses affecting their local areas.

TABLE 2. WILLETT'S ABSOLUTE CLASSIFICATION SYSTEM FOR AMERICAN AIR MASSES

Symbol	Source Region
PC	Alaska, Canada, Arctic
NPC	PC air modified in U.S.
PP	North Pacific Ocean
NPP	PP air modified in U.S.
PA	Cold portions of North Atlantic
NPA	PA air modified over warm North Atlantic
TC	Southern U.S. and Northern Mexico
TG	Gulf of Mexico and Caribbean
NTG	TG air modified over U.S. or North Atlantic
TA	Middle Atlantic
NTA	TA air modified over U.S. or North Atlantic
TP	Middle North Pacific
NTP	TP air modified over U.S. or North Pacific
TS	Subsiding air from upper levels of semi-permanent highs in the southern part of the westerlies.

Showalter also observed that neither system adequately identified air mass thermodynamic properties. When examining frequency distribution charts of equivalent potential temperature, he found that modifying influences cause large variation about the mean temperatures for each air mass, but that the frequency distributions appear normal. This led him to consider an air mass classification system which would use equivalent potential temperature to identify heat and moisture content, and relative humidity to identify the degree of saturation. He never fully developed this system because of the large number of possible combinations, the lack of a stability indicator, and the fact that an air mass type might have no geographical significance.

Based on the work by Showalter and that of Palmén (1948), who examined the wind and temperature distributions in the westerlies over North America, McIntyre (1949), developed temperature frequency histograms for seven North American and British stations at the 700mb, 500mb, 400mb, and 300mb levels. He believed that the polar front, which is a sloping baroclinic zone, should be made apparent by the presence of double maxima on these frequency histograms. When he found that these two maxima were evident, he postulated that their relative proportions represented the percent of time that the polar front was north or south of the individual stations. McIntyre also examined the lapse rates between different pressure levels at each station providing additional evidence to support his reasoning.

Berggren (1952) examined McIntyre's study, and while agreeing that frontal surfaces should cause double maxima in the temperature frequency distribution, he added that an inversion which repeatedly changes elevation over a station would also exhibit such a temperature frequency curve. Berggren extended McIntyre's frequency histograms to the 250mb, 200mb, 170mb, and 150mb levels searching for evidence of a high-tropospheric or low-stratospheric front. Like

McIntyre, he also found evidence of double maxima which again indicated that this method provides a means for examining a sloping baroclinic field. Berggren accepts the adequacy of this method by indirect logic even though the statistical evidence for its validity is inconclusive.

Essenwanger (1954) demonstrated that surface temperature frequency distributions are mixtures of normal distributions each representing a different air mass. He analyzed frequency distributions for temperature and vapor pressure at Karlsruhe, Germany, finding evidence for five separate air mass types. Essenwanger concluded that this method provides an adequate means for examining the frequency and thermal/moisture characteristics of air masses in Europe.

Bryson (1966) developed a partial collective method for analyzing air mass frequencies based on the research conducted by Essenwanger. Assuming that different air masses display different mean characterisitics and that daily maximum temperatures are representative of an air mass, he first developed monthly frequency curves of maximum temperatures at some 120 Canadian and U.S. stations for the 10-year period 1948 through 1957. As anticipated, these frequency distributions are multimodal and appear to be made up of mixtures of normal curves with differing mean characteristics. Bryson then developed a graphical means of separating these mixed normals. In order to test the validity of his assumption that the individual normals represent separate air masses, Bryson compared his results with the air mass frequencies obtained by an independent trajectory method. The distributions of air mass frequencies obtained by both methods were in general agreement.

Davis (1981) used a computerized cluster analysis technique developed by Wolfe (1971) to investigate the possibility of developing a simplified European air mass scheme. Davis examined the frequency distributions for potential temperature, equivalent potential temperature, temperature and mixing ratio, using five years of 850mb data at Berlin, Germany. Only one winter air mass and two summer air masses were found using θ_e which was assumed to be the most effective air mass discriminator in a single variate analysis. Davis noted as possible explanations the limited data set and the likelihood of similar equivalent potential temperatures for cold maritime air and warm continental air.

An examination of the mean 850mb data over Berlin as determined by Geb (1981) supports the probability of similar equivalent potential temperatures in two different air masses. In January, the mean values range from 16.3°C to 15°C for warm continental subpolar air and from 15°C to 14°C for maritime subpolar air. Davis found that these two air masses accounted for 34 percent of the air masses occurring at 850mb over Berlin in November and December during 1976-8.

A similarity also existed in the mean values for maritime Arctic air, 5°C-6.2°C, and continental subpolar air, 7°C to 5.6°C, which accounted for 23 percent of the air masses. In the 1971-76 data, however, Wolfe's program indicated that a single air mass was more likely than these two large distributions with mean temperatures some 10°C apart.

Davis also examined bivariate frequency distributions for potential temperature and mixing ratio at 850mb over Berlin. Wolfe's program was more successful in separating air masses using these distributions and was able to discern four January air masses with mean equivalent potential temperatures of 10.8°C, 13.5°C, 15.7°C, and 19.7°C.

In America, as the upper air observational network developed in the 1950s and 60s, forecasters began to rely on their local upper air soundings for vertical temperature and moisture profiles placing less emphasis on air mass analysis. General air mass analysis techniques are still taught in basic meteorology programs, but they are no longer used by daily weather forecasters who prefer the readily available observed data. Climatologists in America, however, have continued to refer to Bergeron's classification system as it relates to the climatic regimes dominating North America.

CENTRAL EUROPEAN AIR MASSES IN WINTER

According to Schinze (1932), there are seven major source regions for air masses affecting Central Europe in winter. The air masses and their source regions include continental tropical air from North Africa, maritime tropical air from the Eastern Atlantic, maritime polar air from the North Atlantic, continental polar air from North America and inner Russia, and Arctic air from Greenland and northern Russia. Byers (1944) examines the vertical equivalent potential temperature profiles for each of these air mass types and discusses their stability characteristics. Black (1970) provides an excellent discussion of European air masses which is summarized in the following paragraphs.

Continental tropical air rarely influences Central Europe during winter because of the Alpine region which effectively blocks southerly flow into Europe.

Maritime tropical air which originates in the tropical latitudes of the Eastern Atlantic must travel a long distance before reaching Europe. While maintaining its high humidities, this air is gradually cooled until it reaches Europe with average surface temperatures near 4°C. Because of the consistent cooling from below, maritime tropical air reaching Central Europe is very stable in the lower levels.

The stability of maritime polar air, on the other hand, is dependent on its trajectory. A north to south trajectory will result in heating from the surface and instability, while maritime polar air moving from west to east will become more stable due to cooling from below. All maritime air which stagnates over Central Europe will eventually become very stable due to repeated radiational cooling at the surface resulting in widespread low cloudiness and fog.

Continental polar air which originates over North America will be well modified by the time it reaches Europe due to its long over-water trajectory. It arrives as a relatively warm, moist air mass near convective equilibrium.

Continental polar air masses which develop over the snow-covered regions of eastern Europe and Asia are characterized by low temperatures (-7°C), low humidities, and stable lapse rates. When these air masses move into central Europe, they absorb heat and moisture from below, but not enough to warm them appreciably. The added moisture and turbulent mixing results in stratocumulus clouds.

Maritime Arctic air which reaches central Europe from Greenland has traveled only a short distance over water and is consequently modified only in the lower layers. This air is relatively warm and humid in the lower atmosphere causing instability, but it is extremely cold above 1,600 m.

Continental Arctic air originates over Northern Russia and the Barents Sea and is the coldest of all European air masses. In central Europe, continental Arctic air typically has equivalent potential temperatures at the surface near 0°C increasing gradually to 20°C at 500 mb.

The Institute for Meteorology at Berlin, Geb (1981), has developed an air mass classification system which is based on the surface character and latitude of the source region, the stability and turbidity of the air mass, and whether the air is colder or warmer than the underlying surface. Unfortunately this system, which recognizes 18 different air mass types in central Europe, Table 3, is unusable to the Atmospheric Sciences lab researchers because aerosol extinction cannot be resolved into this many subdivisions.

TABLE 3. GERMAN AIR MASS CLASSIFICATION SYSTEM

Symbol	Characteristic	Source Region
cA	Continental Arctic Air	North Siberia, Arctic
xA	Arctic Air	Northern Europe, Arctic
mA	Maritime Arctic Air	North Sea, Arctic
cP	Continental Subpolar	Russia (Subpolar)
xP	Subpolar Air	Northern Europe (Subpolar)
mP	Maritime Subpolar	North Atlantic (Subpolar)
cPs	Warm Continental Subpolar	Modified Over Continental Europe
xPs	Warm Subpolar	Stagnant Over Europe
mPs	Maritime Warm Subpolar	Modified Over Subtropical Sea
cSp	Continental Mid-Latitude	East Europe
xSp	Continental Mid-Latitude	West Europe
mSp	Maritime Mid-Latitude	North Atlantic (Mid-Latitude)
cS	Continental Subtropical	South Eastern Europe
xS	Subtropic	Southern Europe
mS	Maritime Subtropical	Atlantic (Subtropical)
cT	Continental Tropical	Africa
xT	Tropical	Mediterranean
mT	Maritime Tropical	Atlantic (Tropical)
(Fr)	Mixed Air Near Front	

EUROPEAN TOPOGRAPHIC INFLUENCES

The primary influence on central European air masses is the Alpine region which keeps most of the continental and maritime tropical air masses from entering central Europe. There are also two low, 800 meter, mountain ranges in central Germany which influence the number of air masses reaching the two southernmost stations analyzed in this study. These are the Schwarzwald range which runs north-south between Stuttgart, Germany, and Nancy, France, and the Thuringe.rwald range which lies between Stuttgart and Berlin. North of these two mountain ranges, the European plains stretch west to the Atlantic and north to the North Atlantic and Baltic Sea.

DATA

Five years of daily upper air soundings for six European stations were available for developing the frequency distributions required in this study. The stations and their periods of record are listed in Table 4.

TABLE 4. 12Z RAOB DATA BASE (JAN, OCT, NOV, DEC)

STATION	LOCATION LATITUDE / LONGITUDE	ELEVATION	YEARS
POZNAN, POLAND	52°25' N / 16°50' E	100 M	1973-1977
NANCY, FRANCE	48°41' N / 6°13' E	250 M	1973-1977
DEBILT, NETHERLANDS	52°06' N / 5°11' E	8 M	1973-1977
ST. HUBERT, BELGIUM	50°02' N / 5°24' E	600 M	1973-1977
STUTTGART, F.R.G.	48°50' N / 9°12' E	400 M	1971-1975
BERLIN, G.D.R.	52°28' N / 13°24' E	50 M	1971-1975

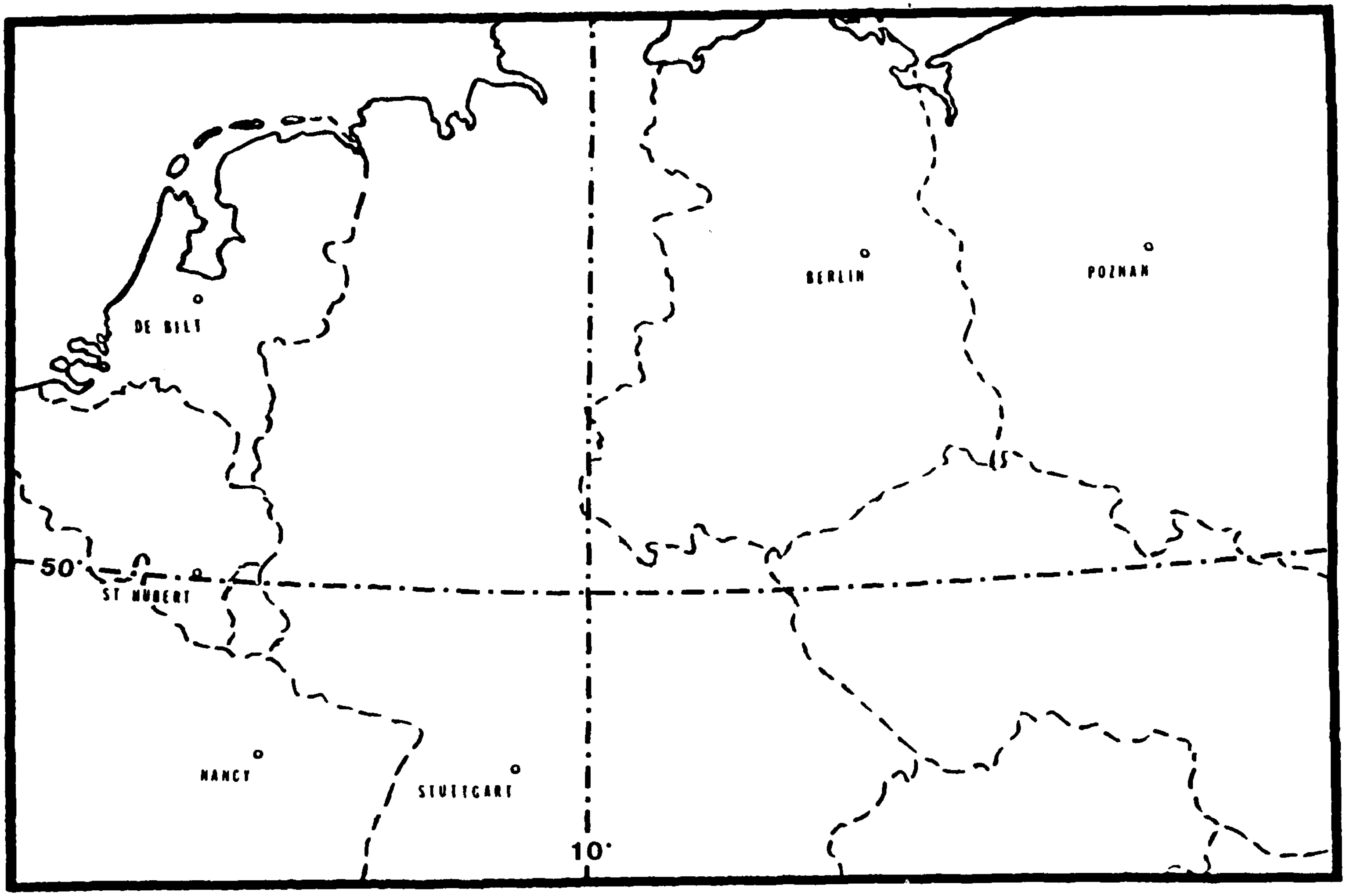

FIGURE 1. STATIONS IN 12 Z RAOB DATA BASE

The stations were selected because they represented the widest horizontal dispersion available, and because each had five consecutive years of 12Z daily upper air soundings. Unfortunately, 1976 and 1977 data were not available for the two German reporting stations.

Because there were only five years of data available, October and November were combined to represent the autumn months, and December and January were combined to represent winter. This effectively doubled the number of observations in the two data sets, greatly enhancing the statistical significance of the results.

Temperature and dewpoint values at the surface, 850mb, 700mb, and 500mb levels and the surface pressure were extracted from the RAOB data base for this study. Because this involved manually manipulating some 36,000 entries, the data had to be checked for errors before proceeding. This was accomplished through a short program designed to flag large, day-to-day pressure and temperature variations and superadiabatic lapse rates. These flagged observations were then individually inspected for accuracy.

DEVELOPING FREQUENCY DISTRIBUTIONS

The data base in Table 4 was developed into frequency histograms for mixing ratio, potential temperatures, and equivalent potential temperatures, and bivariate frequency distributions for mixing ratio versus potential temperatures. Values for these meteorological parameters at each pressure level were calculated in the following manner. First, the saturation vapor pressure for the temperature was found using Tetens' (1930) empirical formula

$$e_s = 6.11\text{mb}*10^{\,7.5\,T/(T+237.3)},$$

where e_s is the saturation vapor pressure and T is the temperature in degrees Celsius. Next, T_d, the dew-point temperature was substituted for T in Tetens' formula. This yielded the vapor pressure, e, since the dew-point temperature is the temperature at which observed vapor pressure is equal to saturation vapor pressure. Then the relative humidity, f, was found as the ratio of vapor pressure to saturation vapor pressure,

$$f = e/e_s,$$

as suggested by Byers (1944), and the saturation mixing ratio, w_s, was determined using

$$w_s = .622\ e_s/(P-e_s),$$

where P equals the pressure. This led to the mixing ratio, w, which is equal to the product of the relative humidity and the saturation mixing ratio,

$$w = f\ w_s.$$

Mixing ratio may also be found by the formula

$$w = .622\ e/(P-e).$$

The potential temperature, θ, was then calculated using Poisson's equation

$$\theta = T\ (1000\text{mb}/P)^{.286},$$

where T is in degrees Kelvin and the initial pressure is 1,000mb. The temperature at the lifted condensation level, T_o, was then determined by Barnes' (1968) formula

$$T_o = T_d - (.001296\ T_d + .1963)\ (T-T_d) + 273.16.$$

Calculation of the equivalent potential temperature, θ_e, followed, using Rossby's (1932) equation

$$\theta_e = \theta_d\ e^{(L_o w/C_p T_o)},$$

where L_o is the heat of condensation at the temperature, T_o, C_p is the specific heat of dry air under constant pressure, and θ_d is the partial potential temperature of the dry air. The difference between θ and θ_d is assumed small as described by Saucier (1955) allowing θ to be substituted for θ_d. The resultant θ_e values are developed into frequency histograms with class intervals of 2°C.

The θ_e frequency histograms are multi-modal and separate easily into Essenwanger's (1954) partial collectives using Bryson's method, Fig. 5. The frequency histograms were developed for class intervals of 2°C because Bryson (1966) and McIntyre (1950) found that, when temperature data are represented by frequency histograms, there exists a strong preference for even degrees as opposed to odd. McIntyre ascribes this to the observational practice of reporting half degrees to the nearest even degree. An example of the frequency distributions derived from the 2° interval histograms before filtering and smoothing is shown in Fig. 2.

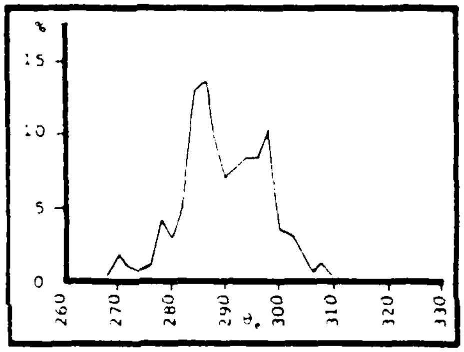

FIGURE 2. UNFILTERED AND UNSMOOTHED.

The data were then changed to percent frequencies and filtered as suggested by Bryson (1966) using the formula

$$Y_x' = 100(.25Y_{(x-1)} + .5Y_x + .25Y_{(x+1)})/N,$$

where N is the number of observations and $Y_{(x-1)}$, Y_x, and $Y_{(x+1)}$ are three consecutive ordinate values. Ordinate values corresponding to θ_e values between the two degree intervals were then approximated using a five point Lagrangian interpolation formula of the form

$$Y_{(x)} = \frac{(x-x_1)(x-x_2)\ldots(x-x_5)}{(x_o-x_1)(x_o-x_2)\ldots(x_o-x_5)}Y_o + \ldots + \frac{(x-x_o)(x-x_1)\ldots(x-x_4)}{(x_5-x_o)(x_5-x_1)\ldots(x_5-x_4)}Y_5$$

in order to smooth the computer plotted frequency curves. Fig. 3 and 4 show the results of smoothing the frequency curves before filtering the data and the final smoothed and filtered data which was used in the partial collective analysis.

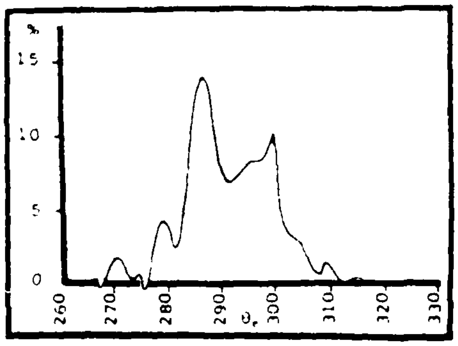

FIGURE 3. SMOOTHED BUT UNFILTERED.

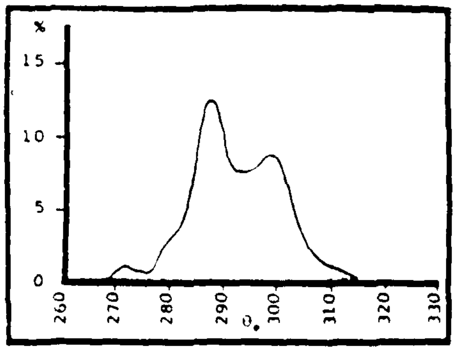

FIGURE 4. SMOOTHED AND FILTERED.

SEPARATING THE MIXED NORMALS

The method for separating the mixtures of normal distributions into partial collectives is based on Bryson's (1966) simplification of Essenwanger's (1954) original technique. Bryson suggests two possible methods for constructing the partial collectives. The first involves selecting a prominent peak in the curve, determining the ordinates for one unit above and below the peak, referring to a table of normal ordinates to estimate standard deviation, constructing the normal from these estimates, and subtracting this normal from the frequency distribution. This process is repeated on the residue until no further peaks are observed. Bryson's second method is to build "families" of normal curves of many standard deviations and modal ordinates. These are fit to the frequency distributions manually on a light table and the closest fitting normal is repeatedly subtracted from the frequency curve and its residue until the residue is at a minimum. The proportion of each normal is then determined by planimetering.

It was found in the current study that, for each frequency distribution, Bryson's first method takes about 6 hours to complete. Sielaff (1980) used Bryson's second method to study the summer air masses in northwest Oregon and found that it took him between 2 and 4 hours to analyze each graph. By using the interactive computer program developed here, this process was completed in 15 to 25 minutes. Bryson notes that a computer method for least squares fitting of a series of normal curves is available, Johnson (1966), but such an approach denies the researcher the ability to inspect each partial collective subjectively as he must do to insure physically reasonable results.

The interactive computer program allows the researcher to examine the smoothed and filtered frequency curves which are displayed on a CRT screen. Mean θ_e (M), standard deviation (S), and peak ordinate (P) values for a partial collective are then estimated and fed into the computer which calculates the normal curve (N) for θ_e between 259 K and 330 K using the following subroutine written in HP Basic,

```
X = 259
FOR I = 1 to 142
X1 = X-M
N(I) = P*EXP((X1/S)^2/-2)
X = X+.5
NEXT I
```

This normal is then displayed over the frequency curve and modified according to its fit by the researcher. Once an accurate fit is obtained, the partial collective is subtracted from the frequency distribution and the residue is examined. If the residue is unacceptable, the partial collective is added back in and a new partial collective is tried. This process is repeated until a set of normals is developed which, when subtracted from the frequency curve, results in an acceptably flat residue curve. The weights (W) or population proportions for each of the partial collectives are calculated by the formula, Sielaff (1960),

$$W = PS\sqrt{2\pi}/2,$$

where division by two is necessary because of the two degree class intervals. These weights are then summed and subtracted from 100 giving a percentage value for the residue.

For this study, if the absolute value of the residue was greater than one percent, one or more of the partial collectives were modified to improve the fit. Each station's frequency distributions for the different levels were separated into partial collectives independently at first in order to avoid biasing the results. After all of the frequency curves had been analyzed, they were compared subjectively both vertically at the different levels and horizontally from station to station. Distributions containing partial collectives which appeared out of place in the results were reanalyzed. The final sets of partial collectives were then examined statistically to insure that the individual normal distributions were from separate populations as recommended by Snedecor and Cochran (1967). This is accomplished by testing the null hypothesis that there is no difference between the population means. Setting the mean θ_e for one normal equal to another,

$$M_{(\bar{\theta}_{e,1}-\bar{\theta}_{e,2})} = 0 \quad \text{and} \quad S_{(\bar{\theta}_{e,1}-\bar{\theta}_{e,2})} = \sqrt{\frac{S_1^2}{N_1} + \frac{S_2^2}{N_2}}\ ,$$

where N_1 and N_2 represent the number of observations. The standardized variable, Z, is calculated using the equation

$$Z = \frac{\bar{\theta}_{e,1} - \bar{\theta}_{e,2}}{S_{(\bar{\theta}_{e,1} - \bar{\theta}_{e,2})}} .$$

These Z values in all cases lay outside the range of -2.58 to 2.58 which is the 99 percent confidence level for significantly different populations, Snedecor and Cochran (1967).

RESULTS

Results of the European air mass analysis indicate that at the surface there are six major air masses affecting central Europe in the fall and five in the winter. At 850mb, there are five air masses in the fall and winter, but one of the winter air masses reaches only as far north as Nancy, France. At 700mb in the fall and winter, there are six and five air masses respectively, with the coldest air reaching only the stations in the west and north and the warmest air reaching only the easternmost stations. During the fall and winter at 500mb, five air masses occur in central Europe, but one of these reaches only the northernmost stations and another occurs only in the fall at the two southernmost stations.

The air mass types identified by the partial collective analyses are numbered consecutively from coldest to warmest and then assigned air mass classifications, ie. cP, mP, etc., on the basis of their relative frequencies from station to station, Fig. 13-16, and on the basis of mean θ_e values as compared to Geb (1981). In their classical descriptions of air masses, Rossby (1932) and Byers (1944) described θ_e values as decreasing with altitude for mT air, constant with altitude for mP air and increasing with altitude for cP air. Although normally true, this is not always the case in this study as may be seen by examining cP air in the fall which is nearly constant with height.

TABLE 5. PARTIAL COLLECTIVES FOR OCT/NOV AT SURFACE*

		DeBilt	Berlin	Poznan	St. Hubert	Nancy	Stuttgart
	$\bar{\theta}_e$	283.0	278.0		283.0	281.8	282.0
I	S	3.3	3.5		3.1	2.8	3.7
	%	5.8	5.3		7.8	6.3	7.0
	$\bar{\theta}_e$	293.0	290.7	291.7	291.0	291.3	292.7
II	S	3.8	5.3	6.0	2.8	3.1	3.6
	%	48.1	71.1	76.0	31.9	28.4	58.2
	$\bar{\theta}_e$	299.4	299.0	299.8	298.0	298.0	300.3
III	S	2.3	3.0	2.8	2.8	3.3	2.3
	%	21.3	17.3	10.9	31.6	36.4	18.4
	$\bar{\theta}_e$	306.4	308.3	307.8	305.1	306.7	306.0
IV	S	3.5	2.8	2.5	3.0	2.7	2.8
	%	18.9	7.0	8.1	22.9	20.6	10.2
	$\bar{\theta}_e$	316.0		316.5	316.0	314.5	313.7
V	S	2.8		2.5	3.2	2.0	3.55
	%	6.0		4.4	6.0	4.0	6.7
	$\bar{\theta}_e$					322.0	
VI	S					3.0	
	%					4.5	

*In Tables 5-12, $\bar{\theta}_e$ is mean equivalent potential temp, S is standard deviation, and % is percent of observations.

There are six air masses identifiable through partial collective analysis during Oct/Nov at the surface.

Type I air appears to be maritime Arctic air which invades central Europe from the Northwest. It has a mean θ_e value near 280 K and occurs about six percent of the time.

Type II air is continental polar air which apparently spreads southwestward from Poznan and has $\bar{\theta}_e$ near 291 K.

Type III air is maritime polar air which seems to move in from the North Atlantic with $\bar{\theta}_e$ near 299 K.

Type IV air is maritime subtropical air which appears to originate over the eastern Atlantic with $\bar{\theta}_e$ near 306 K.

Types V and VI are both maritime tropical air masses which occur infrequently in central Europe.

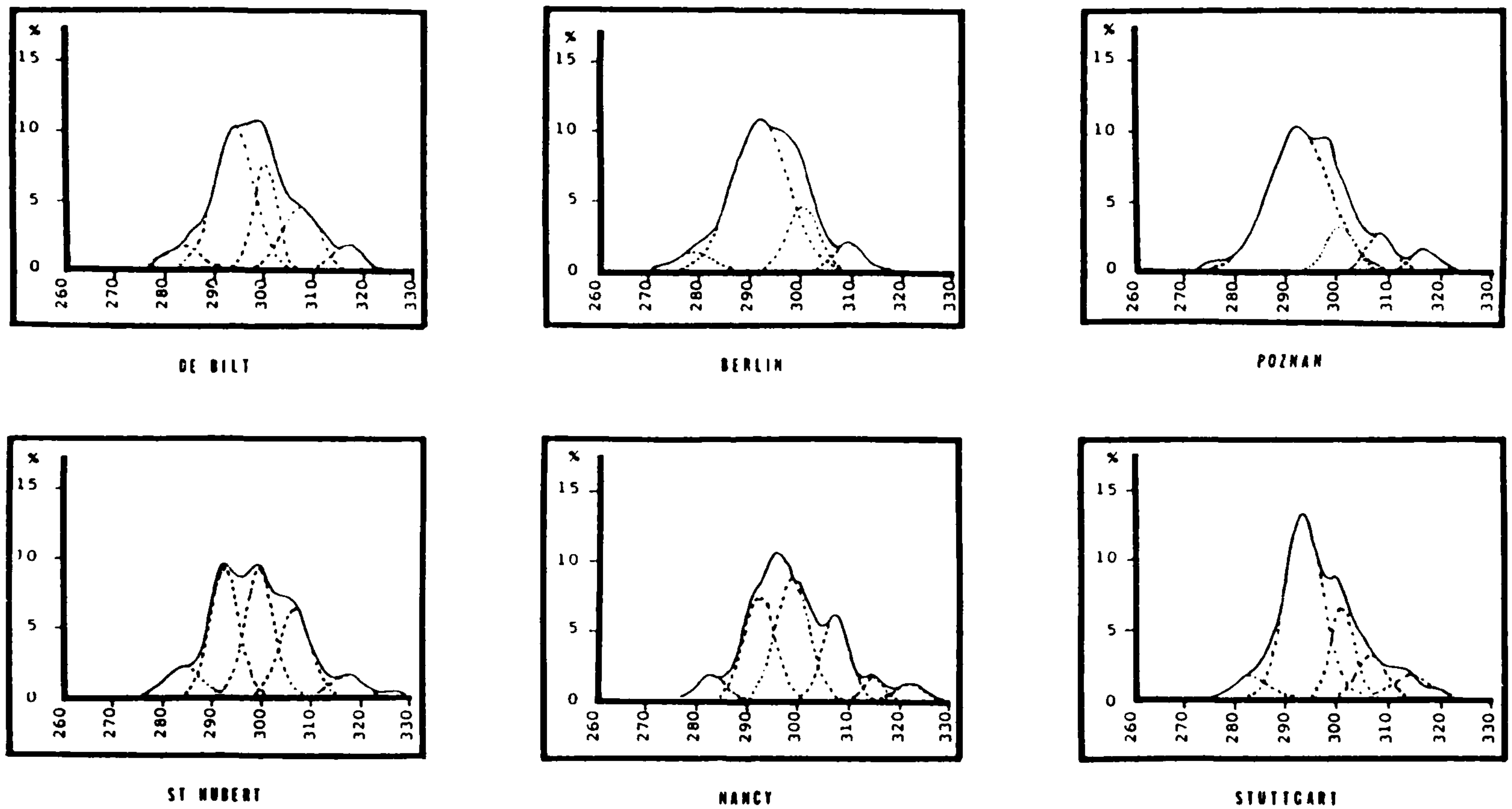

FIGURE 5. SURFACE GRAPHS FOR OCTOBER AND NOVEMBER.
(Abscissa values for figures 5-12 represent θ_e in K)

TABLE 6. PARTIAL COLLECTIVES FOR OCT/NOV AT 850 mb.

		DeBilt	Berlin	Poznan	St. Hubert	Nancy	Stuttgart
I	$\bar{\theta}_e$	282.4	283.2	282.0	284.5	283.0	282.0
	s	2.5	3.3	2.6	2.5	3.0	3.0
	%	2.8	16.5	7.5	6.3	3.8	3.8
II	$\bar{\theta}_e$	292.0	292.2	291.7	292.4	294.1	292.3
	s	3.2	3.35	3.6	2.55	4.1	4.0
	%	43.7	45.3	42.4	29.4	48.3	46.6
III	$\bar{\theta}_e$	298.5	300.0	299.5	298.5	301.6	300.3
	s	2.7	2.6	3.3	2.5	2.0	2.7
	%	29.8	22.8	19.9	28.5	17.5	30.1
IV	$\bar{\theta}_e$	305.7	306.7	307.5	305.2	306.0	306.0
	s	3.5	3.5	6.5	2.9	2.0	2.2
	%	19.7	15.4	31.0	29.1	15.0	12.7
V	$\bar{\theta}_e$	316.3			314.2	313.0	312.5
	s	2.7			3.4	3.5	2.4
	%	4.1			7.7	14.5	7.4

Five major fall air mass types are evident at 850mb.

Type I air appears to be maritime Arctic air which invades Europe from the North Sea and Artic. It occurs most frequently at Berlin and has a $\bar{\theta}_e$ near 283 K.

Type II air appears to be a combination of continental and maritime polar air and is the most frequent type at all six stations. It has a $\bar{\theta}_e$ of about 292 K and is evenly distributed at all of the stations except St. Hubert. This is probably due to St. Hubert's 600 meter elevation.

Type III air is maritime subpolar air from the North Atlantic which seems to invade Europe from the northwest.

Type IV air is also maritime subpolar air, but this type has been modified over the subtropical Atlantic raising the $\bar{\theta}_e$ some 7 K.

Type V air is maritime tropical air which spreads north and east from Nancy, never reaching Poznan and Berlin.

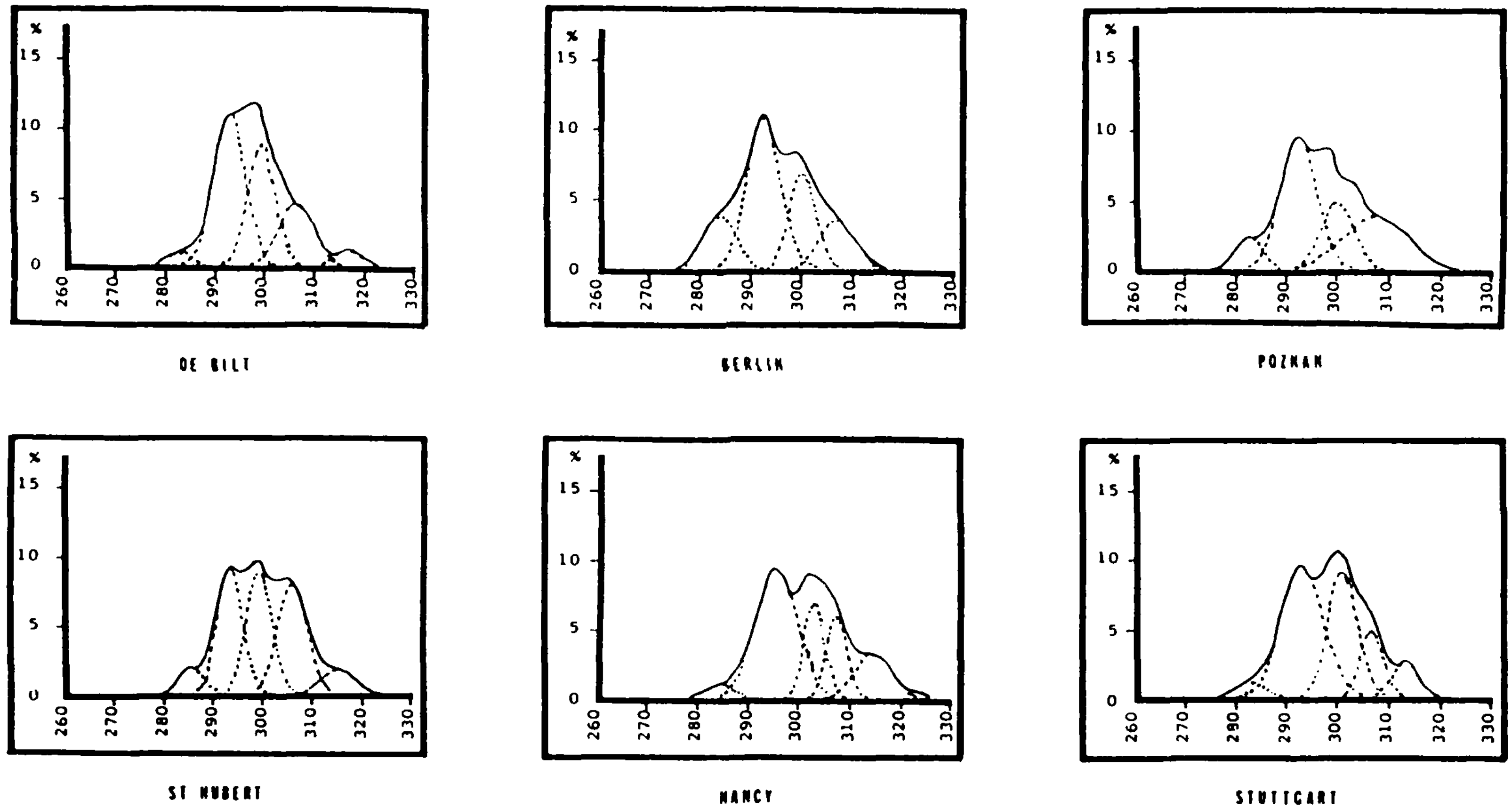

FIGURE 6. 850 mb GRAPHS FOR OCTOBER AND NOVEMBER.

TABLE 7. PARTIAL COLLECTIVES FOR OCT/NOV AT 700 mb.

		DeBilt	Berlin	Poznan	St. Hubert	Nancy	Stuttgart
	$\bar{\theta}_e$		282.3	284.0			283.8
I	s		2.2	3.0			2.5
	%		5.0	6.0			3.1
	$\bar{\theta}_e$	293.0	289.5	293.0	292.0	293.3	294.2
II	s	3.8	2.6	3.2	3.5	5.0	4.7
	%	32.4	15.3	20.1	15.4	21.9	27.7
	$\bar{\theta}_e$	300.0	296.1	298.4	298.5		
III	s	3.0	3.2	2.0	2.7		
	%	27.4	28.9	21.6	25.7		
	$\bar{\theta}_e$	307.0	303.2	305.5	305.0	304.0	305.5
IV	s	3.6	2.5	3.0	3.3	4.8	5.2
	%	34.3	28.8	33.8	29.0	54.7	69.7
	$\bar{\theta}_e$		309.0	312.0	311.0	311.0	
V	s		3.2	3.5	4.3	2.4	
	%		22.1	19.3	29.6	15.9	
	$\bar{\theta}_e$	316.0				317.0	
VI	s	2.4				2.4	
	%	5.7				7.2	

There are six major air masses identifiable with the partial collective method at 700mb during the fall.

Type I is apparently continental Arctic air which reaches only Berlin, Poznan, and Stuttgart with $\bar{\theta}_e$ = 283 K.

Type II is combined maritime polar and continental subpolar air which is fairly evenly distributed across Europe.

Type III is continental subpolar air from Russia which affects northern Europe some 25% of the time with $\bar{\theta}_e$ =298 K.

Type IV air is maritime subpolar air which dominates in the south and is the most frequent fall air mass at 700mb.

Type V air is apparently maritime subtropical in origin because of its high $\bar{\theta}_e$ values. Type V air at DeBilt and Stuttgart is probably combined with Type IV .

Type VI appears to be maritime tropical air, $\bar{\theta}_e$ near 316 K, which reaches only the easternmost stations.

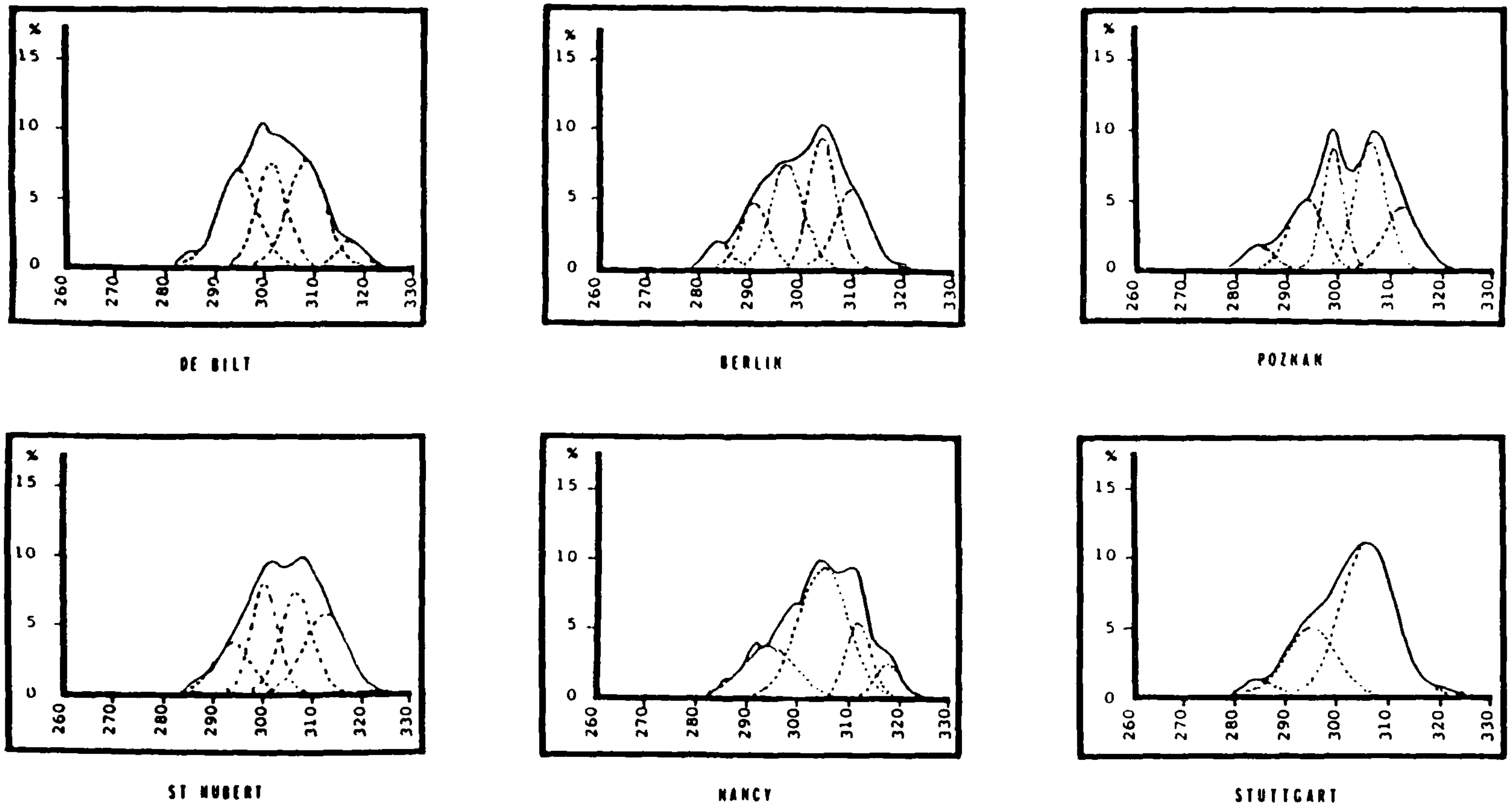

FIGURE 7. 700 mb GRAPHS FOR OCTOBER AND NOVEMBER.

TABLE 8. PARTIAL COLLECTIVES FOR OCT/NOV AT 500 mb.

		DeBilt	Berlin	Poznan	St. Hubert	Nancy	Stuttgart
	$\bar{\theta}_e$		290.5	290.0			
I	S		4.0	5.5			
	%		8.5	6.9			
	$\bar{\theta}_e$	298.4	298.1	297.0	296.2	297.0	296.0
II	S	4.0	3.1	3.2	2.6	3.2	5.0
	%	23.1	13.6	13.2	11.4	14.0	13.8
	$\bar{\theta}_e$	304.9	305.5	306.5	305.0	303.8	303.5
III	S	1.9	3.0	3.7	4.0	1.9	3.0
	%	7.1	28.2	36.2	24.6	13.1	13.2
	$\bar{\theta}_e$					310.0	308.4
IV	S					2.5	1.7
	%					32.0	8.5
	$\bar{\theta}_e$	312.0	312.6	314.2	313.5	317.1	313.1
V	S	5.7	4.2	4.0	4.9	3.6	4.4
	%	70.0	50.5	43.6	63.9	40.6	65.1

Only five air mass types affect Europe at 500mb in winter.

Type I is continental polar air which reaches only the the two northwestern stations with $\bar{\theta}_e$ near 290 K.

Type II is maritime polar air which appears to spread southeastward across central Europe with $\bar{\theta}_e$ values near 297 K.

Type III is continental subpolar air which develops over Russia and spreads southwestward over Europe.

Type IV air is maritime tropical air which reaches only Nancy and Stuttgart in the fall.

Type V air dominates central Europe during October and November at 500mb. It has a maritime subtropical source region and mean θ_e values near 313 K.

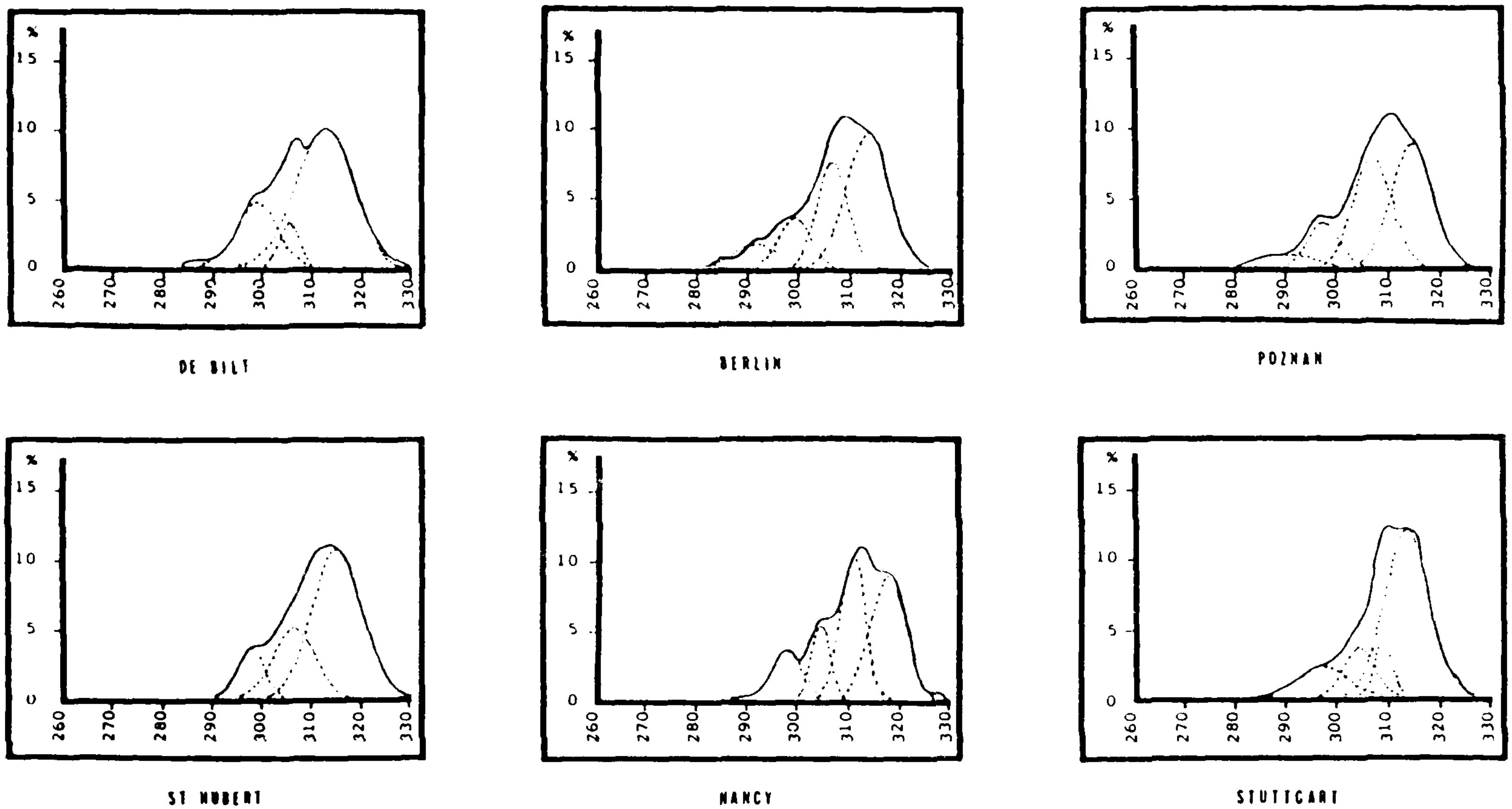

FIGURE 8. 500 mb GRAPHS FOR OCTOBER AND NOVEMBER.

TABLE 9. PARTIAL COLLECTIVES FOR DEC/JAN AT SURFACE.

		DeBilt	Berlin	Poznan	St. Hubert	Nancy	Stuttgart
I	$\bar{\theta}_e$	272.0	272.7	273.2		275.8	274.2
	S	2.2	4.0	2.0		4.2	4.5
	%	2.5	13.5	7.5		8.9	10.7
II	$\bar{\theta}_e$	283.2	282.3	281.0	284.0	284.2	285.0
	S	3.2	3.5	4.4	5.2	2.6	4.2
	%	29.8	33.3	41.9	33.9	40.1	53.7
III	$\bar{\theta}_e$	289.2	289.5	288.0	288.3	290.2	292.0
	S	2.5	4.7	4.3	3.0	2.4	2.5
	%	35.7	53.0	50.1	33.8	18.0	24.1
IV	$\bar{\theta}_e$	294.0			295.5	295.5	
	S	1.95			2.7	2.4	
	%	16.4			24.7	23.8	
V	$\bar{\theta}_e$	298.0			301.8	300.4	299.0
	S	3.0			3.0	3.5	3.5
	%	16.2			7.5	9.7	10.5

During the winter months, there are five major air masses affecting central Europe at the surface.

Type I is continental Arctic air which originates over North Siberia and the Arctic. It apparently moves into Europe with modified θ_e values near 273 K.

Type II air appears to be a combination of maritime Arctic and continental polar air and is fairly uniform in its distribution with $\bar{\theta}_e$ near 283 K.

Type III is maritime polar air which has a southward trajectory into central Europe from the North Atlantic.

Type IV is maritime subpolar air which reaches only the three easternmost stations.

Type V air appears to be from a maritime subtropical source region and affects only the eastern and southern stations.

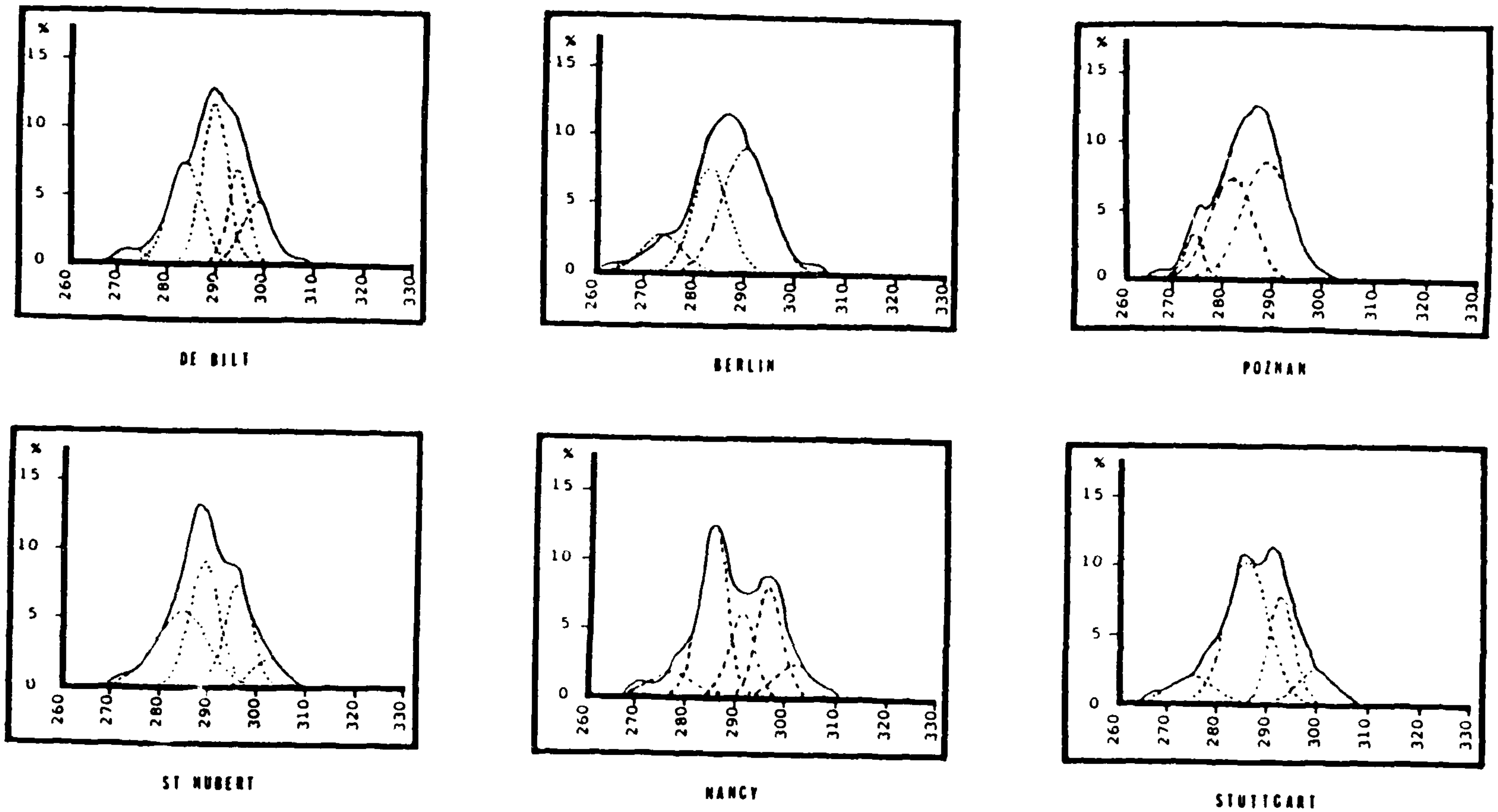

FIGURE 9. SURFACE GRAPHS FOR DECEMBER AND JANUARY.

TABLE 10. PARTIAL COLLECTIVES FOR DEC/JAN AT 850 mb.

		DeBilt	Berlin	Poznan	St. Hubert	Nancy	Stuttgart
I	$\bar{\theta}_e$	283.0	282.3	279.0	283.2		279.8
	s	3.0	2.8	3.0	2.2		3.0
	%	16.9	9.5	10.9	11.4		4.5
II	$\bar{\theta}_e$	290.0	288.5	287.8	288.2	286.0	287.3
	s	3.0	3.0	3.95	2.3	3.7	3.0
	%	38.7	43.2	57.4	20.2	25.5	25.2
III	$\bar{\theta}_e$	296.0	295.0	296.8	293.8	294.0	294.1
	s	2.3	2.9	3.8	2.5	3.0	2.8
	%	23.6	34.2	31.4	33.5	38.4	34.7
IV	$\bar{\theta}_e$	301.7	302.6		300.7	299.5	299.5
	s	3.5	3.8		3.3	2.3	3.4
	%	19.7	12.4		34.3	22.5	34.1
V	$\bar{\theta}_e$					304.5	
	s					2.3	
	%					12.6	

Five air mass types are discernable in the winter at 850mb.

Type I appears to be maritime Arctic and continental polar air combined with $\bar{\theta}_e$ near 281 K.

Type II is continental subpolar air from Russia which appears to spread southwestward over Europe.

Type III is maritime subpolar air with $\bar{\theta}_e$ near 295 K and is fairly evenly distributed over central Europe.

Type IV air dominates in southern Europe, but doesn't reach Poznan. It is apparently maritime tropical in origin with $\bar{\theta}_e$ near 300 K.

Type V is maritime tropical air which only reaches Nancy, France with a mean θ_e of 304.5 K.

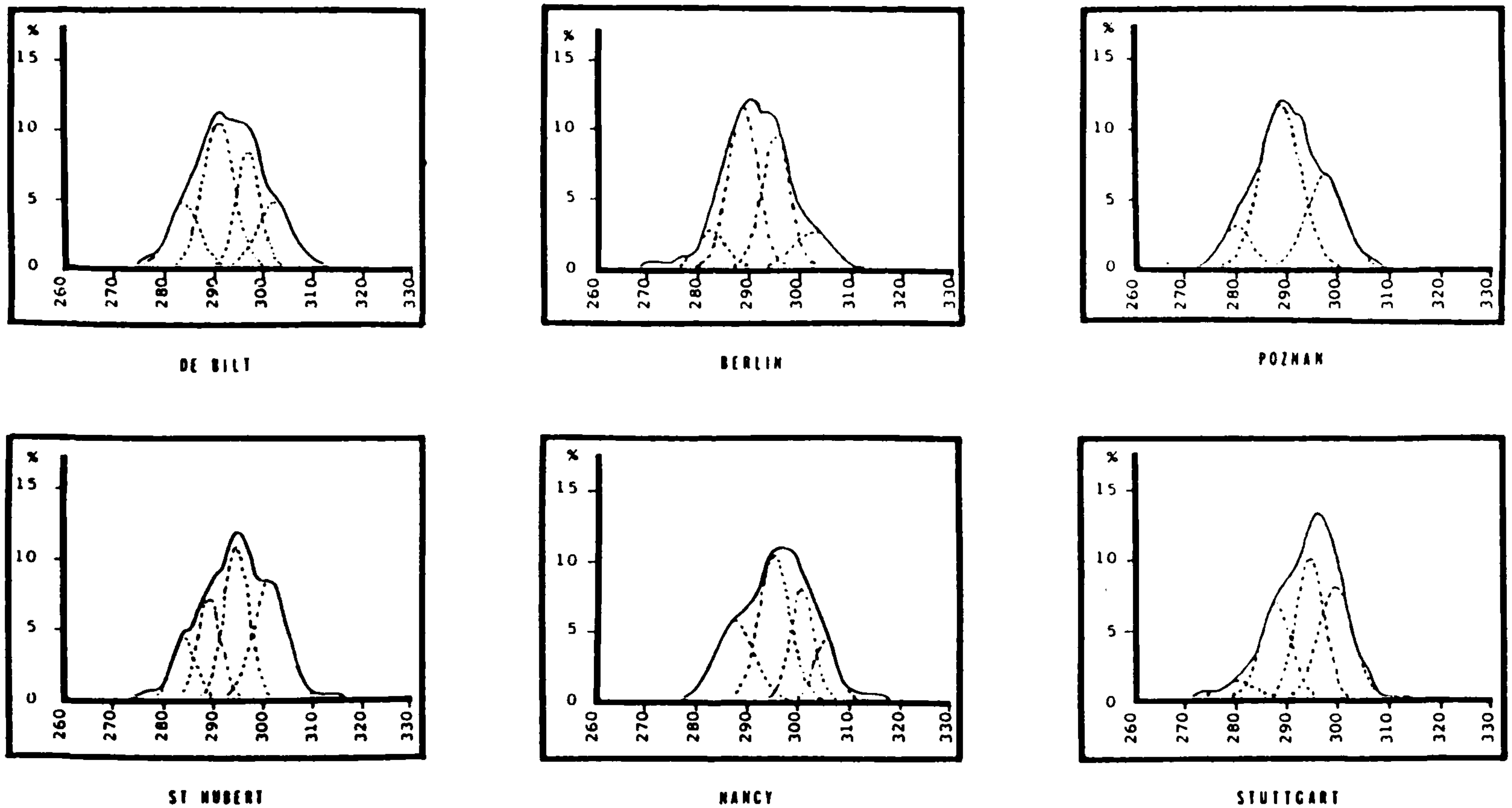

FIGURE 10. 850 mb GRAPHS FOR DECEMBER AND JANUARY.

TABLE 11. PARTIAL COLLECTIVES FOR DEC/JAN AT 700 mb.

		DeBilt	Berlin	Poznan	St. Hubert	Nancy	Stuttgart
I	$\bar{\theta}_e$			282.5			
	S			2.8			
	%			9.1			
II	$\bar{\theta}_e$	285.8	285.0	288.2	290.4	289.0	290.5
	S	2.27	4.5	2.25	3.9	2.5	3.5
	%	10.5	8.5	18.3	25.9	13.2	19.3
III	$\bar{\theta}_e$	290.3	291.8	293.4	295.6	295.7	296.0
	S	2.0	3.5	2.25	3.8	2.8	2.0
	%	17.0	25.0	20.3	15.2	28.1	15.5
IV	$\bar{\theta}_e$	299.8	299.9	300.3	302.2	303.0	301.2
	S	4.9	4.0	3.9	3.2	3.0	3.45
	%	71.9	66.7	51.3	50.1	47.4	64.9
V	$\bar{\theta}_e$				309.3	309.0	
	S				3.3	4.5	
	%				9.5	10.2	

Five winter air masses can be identified at 700mb using the partial collective method.

Type I is continental Arctic air which is about 10° warmer at 700mb than at the surface as described by Byers (1944). Type I air is found only at Poznan and has a mean θ_e of 282.5 K.

Type II is apparently maritime polar air with mean θ_e values near 288 K.

Type III is a combination of maritime subpolar air mainly in the South and continental subpolar air in the Northwest. Its mean θ_e values range from 290.3 K to 296 K.

Type IV is maritime subtropical air, and this air mass type dominates at 700mb in the winter over all of Europe.

Type V is maritime tropical air which only reaches the two southeastern stations.

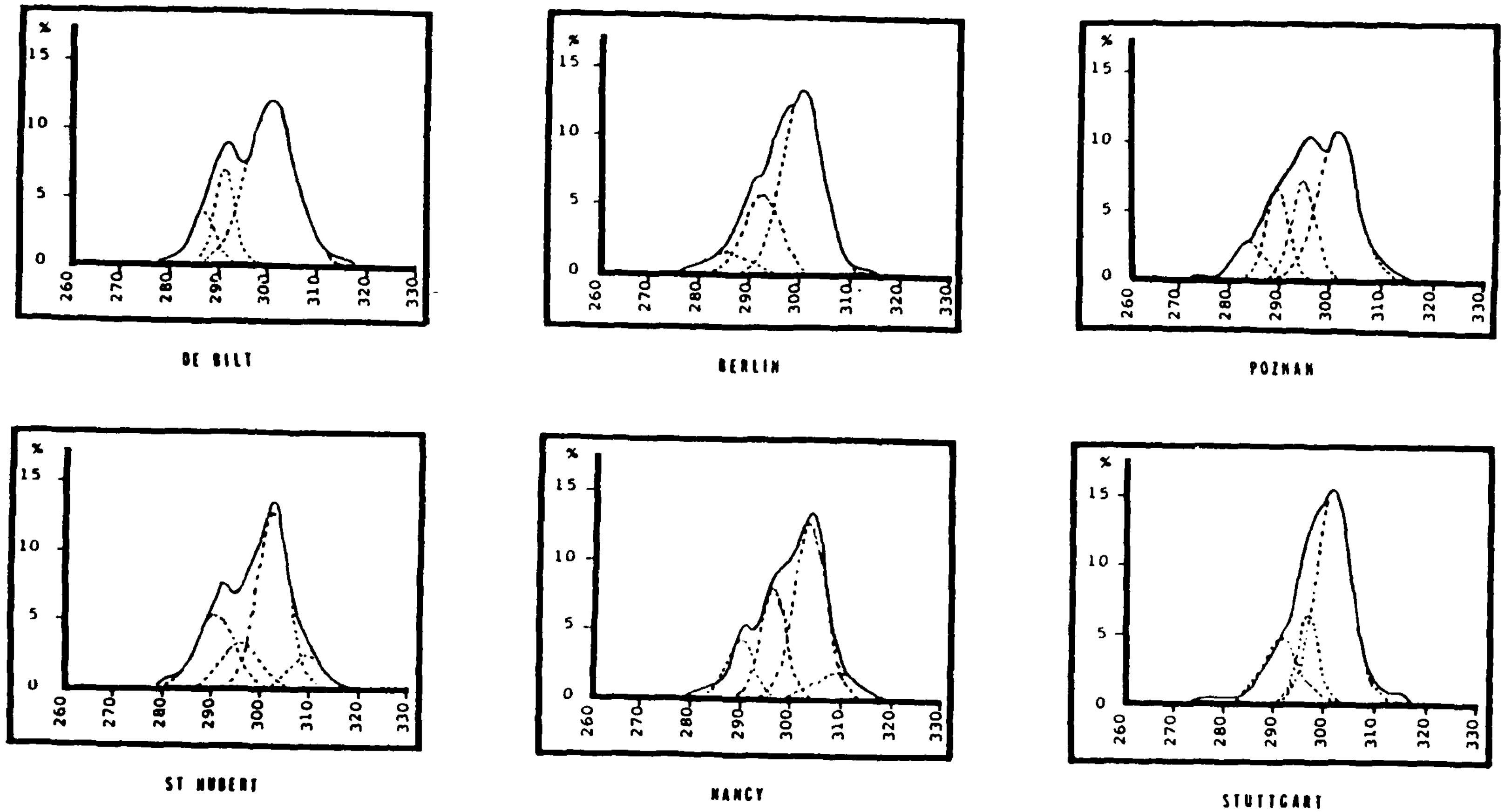

FIGURE 11. 700 mb GRAPHS FOR DECEMBER AND JANUARY.

TABLE 12. PARTIAL COLLECTIVES FOR DEC/JAN AT 500 mb.

		DeBilt	Berlin	Poznan	St. Hubert	Nancy	Stuttgart
I	$\bar{\theta}_e$		284.3	285.5			
	S		2.0	2.6			
	%		1.9	4.9			
II	$\bar{\theta}_e$	292.0	293.7	293.5	293.7		295.3
	S	3.75	3.2	3.0	3.4		2.6
	%	14.1	12.0	16.9	13.6		6.0
III	$\bar{\theta}_e$	301.0	300.2	300.0	302.8	298.0	301.2
	S	3.0	2.6	3.2	3.0	5.0	2.9
	%	16.9	21.2	20.9	22.2	17.5	17.4
IV	$\bar{\theta}_e$	308.0	307.0	306.8	309.4	309.2	307.9
	S	3.9	3.6	4.0	3.75	4.2	3.73
	%	68.4	64.5	57.7	63.9	81.6	76.0

Four air mass types are discernable at 500mb in winter.

Type I is continental Arctic air which originates over North Siberia and the Arctic and is found only at Berlin and Poznan.

Type II is apparently continental polar air which spreads southwestward over Europe, never reaching Nancy.

Type III is maritime subpolar air with $\bar{\theta}_e$ near 300 K and is evenly distributed across central Europe.

Type IV is maritime subtropical air and is the dominant air mass over Europe at 500mb in winter.

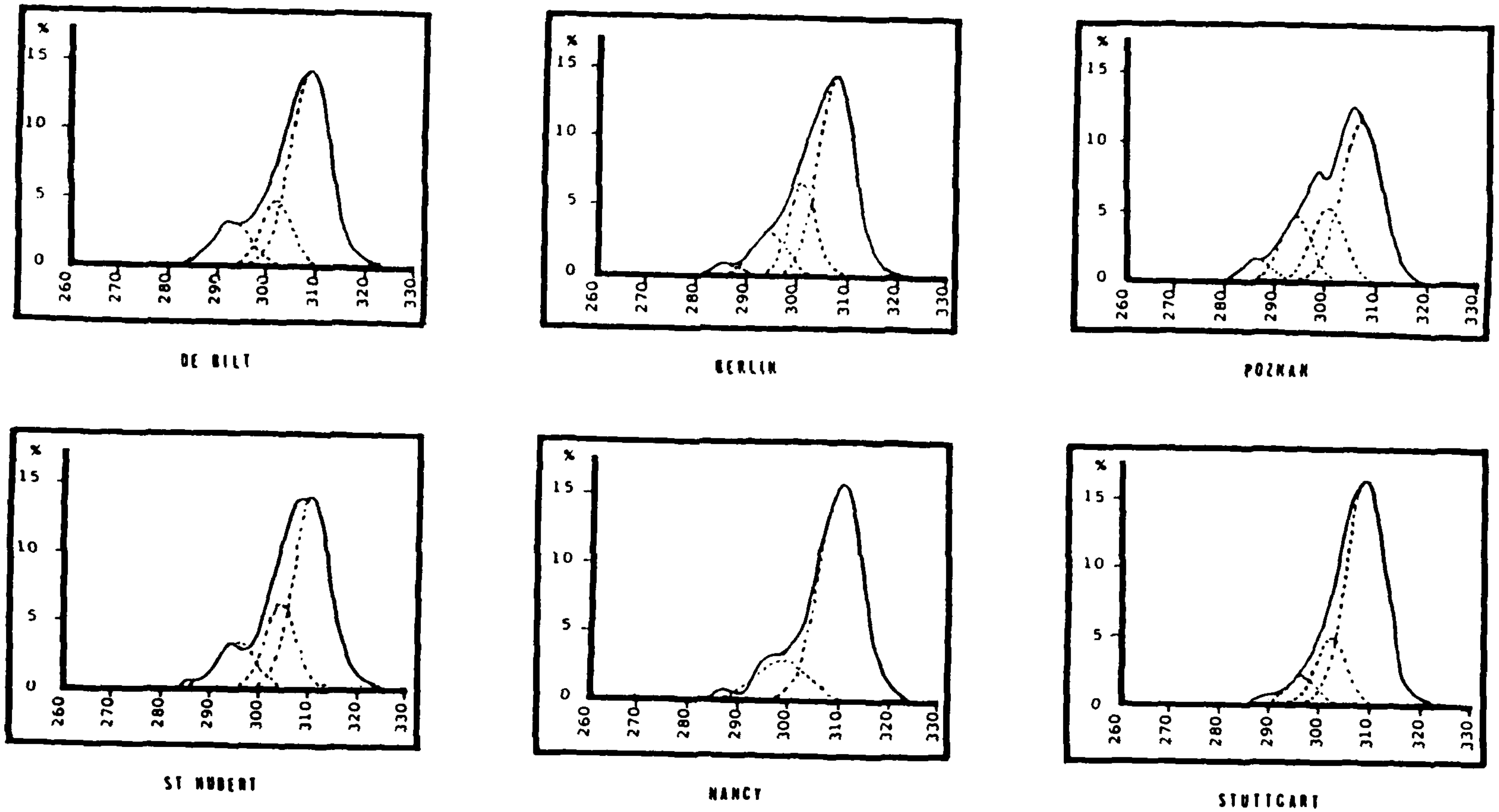

FIGURE 12. 500 mb GRAPHS FOR DECEMBER AND JANUARY.

As already mentioned, the air mass types identified by the partial collective analyses are assigned air mass classifications on the basis of their relative frequencies from station to station. The percent frequencies of occurrence for each air mass type were plotted as shown in Fig. 13-16. It should be noted that these figures do not depict air mass trajectories but simply show where and how often air with similar equivalent potential temperature occurs. Bryson (1966) notes that charts of percent frequencies of occurrence of daily maximum temperatures in the United States and Canada found by the partial collective technique were in general agreement with those found through trajectory analyses, however.

The most frequently occurring surface air mass types, cP and mP are examined during the fall, Fig. 13 and 14, and winter, Fig. 15 and 16. These figures show how easily maritime and continental differentiation becomes. Latitudinal differentiation is more difficult, however, and must frequently be determined through comparison with other air masses present at the same level, ie. polar air is assumed colder than tropical air. The less frequent air mass types were not as easy to analyze and, in many cases, the classifications were based more on the θ_e values found by Geb (1981) than on frequencies of occurrence.

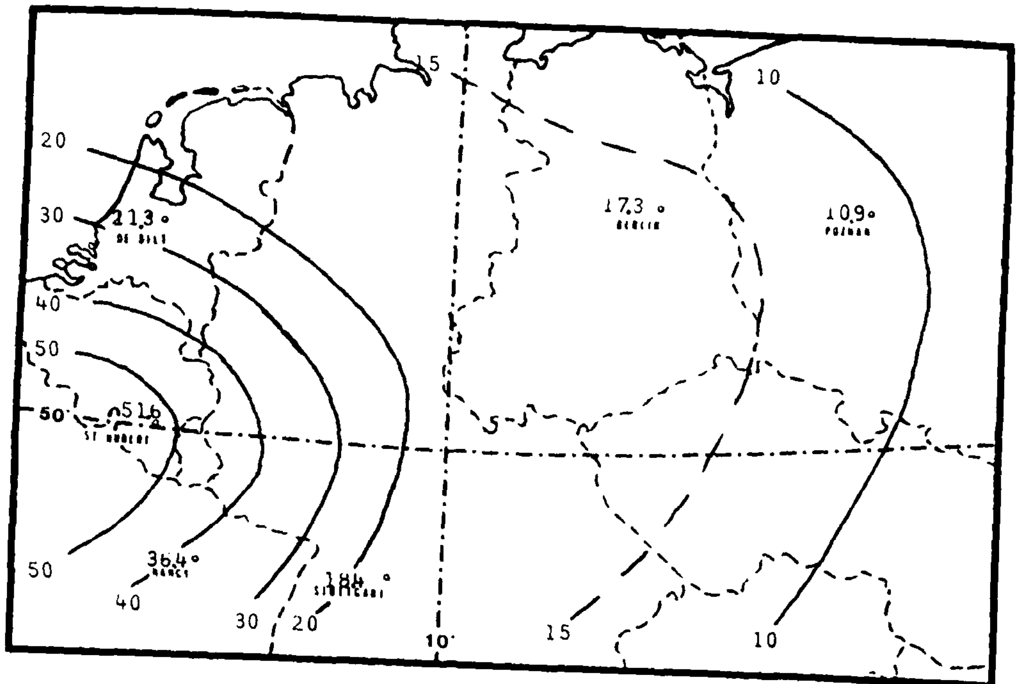

FIGURE 13. SURFACE MAP DEPICTING mP AIR IN THE FALL (VALUES IN FIG. 13-16 REPRESENT % FREQUENCIES)

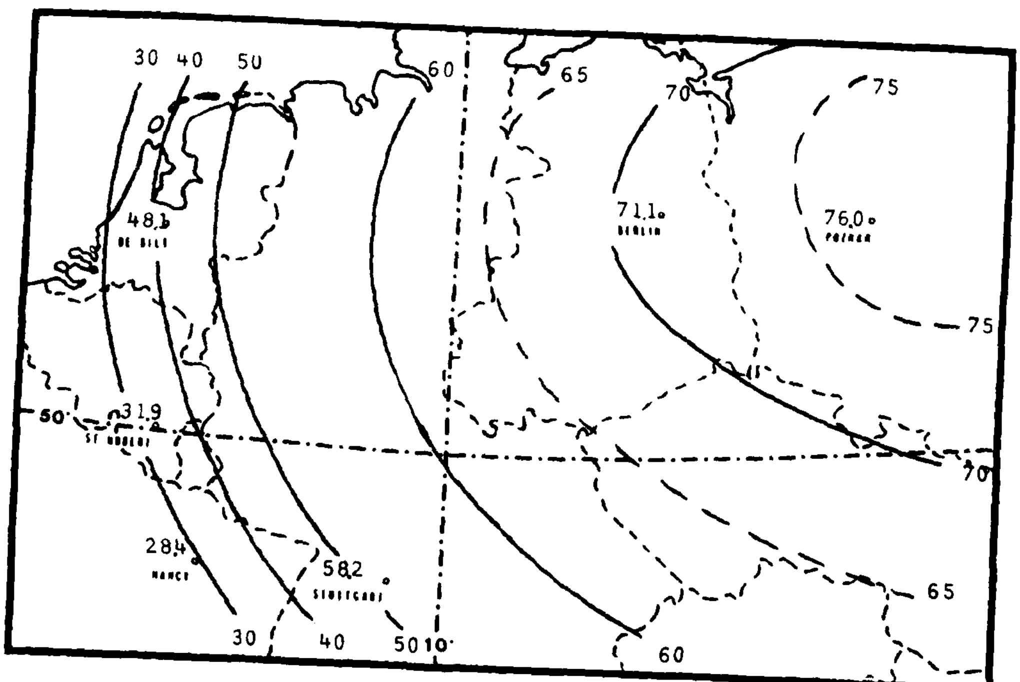

FIGURE 14. SURFACE MAP DEPICTING cP AIR IN THE FALL

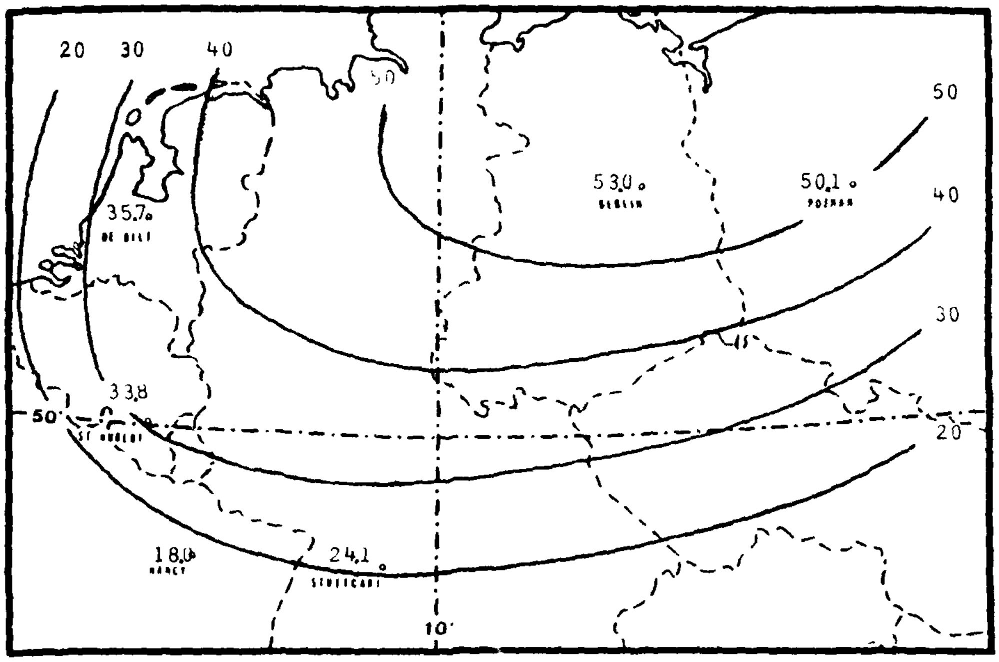

FIGURE 15. SURFACE MAP DEPICTING mP AIR IN THE WINTER

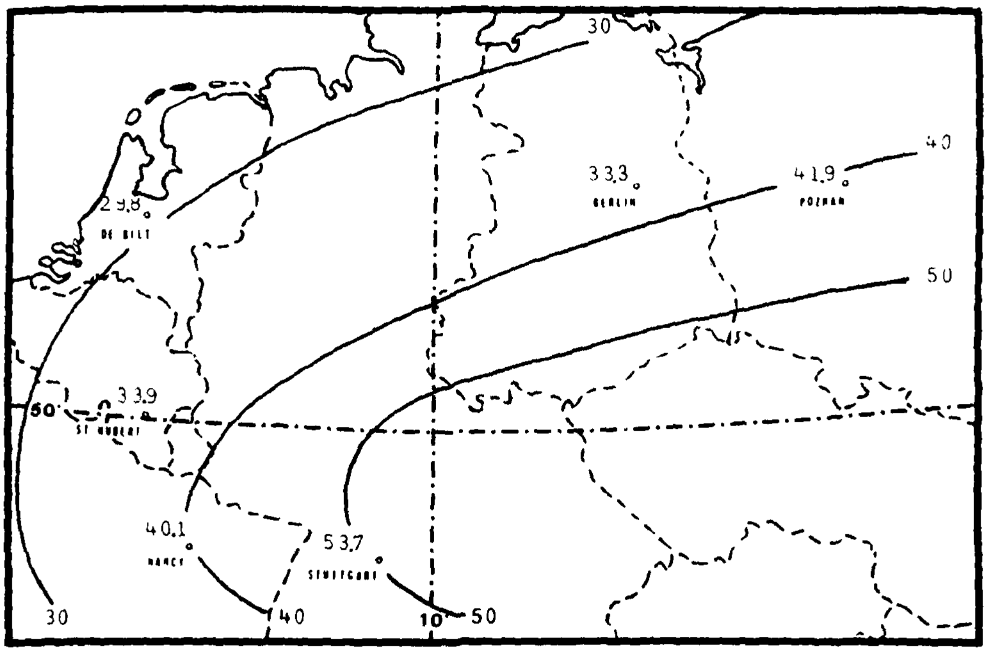

FIGURE 16. SURFACE MAP DEPICTING cP AIR IN THE WINTER

COMPARISON WITH OTHER WORK

Kays (1982) examined the European daily synoptic charts for the period January 1969 to July 1981 and tabulated the eight major air mass types which occurred at 850mb over Berlin, Germany, according to the German system in Table 3. In Tables 13 and 14, Kays' work is combined with Geb's (1981) who determined the monthly mean θ_e values for these same air masses and standard deviations about these means. Their findings are compared to the Berlin 850mb values in Tables 6 and 10.

TABLE 13. BERLIN AIR MASS COMPARISON FOR OCT/NOV.

Geb (1981) and Kays (1982)				Coleman (1982)			
Type	%	$\bar{\theta}_e$ (K)	S	Type	%	$\bar{\theta}_e$ (K)	S
cP	20	291.9-282.6	3.8				
mP	29	298.5-290.4	2.8	II	45.3	292.2	3.35
cT	7	292.0-288.8	?				
mA	10	288.2-282.2	2.6	I	16.5	283.2	3.3
cPs	22	302.0-292.9	2.9	III	22.8	300.0	2.6
mPs	5	308.2-298.7	3.0	IV	15.4	306.7	3.5
cA	5	272.5	large				
mT	1	325.2-319.6	?				

If cP, mP, and cT air are combined in the Geb/Kays data for Oct/Nov because of their similar θ_e values, the results in Table 6 compare favorably with the data compiled by Geb and Kays for a much longer period of record.

TABLE 14. BERLIN AIR MASS COMPARISON FOR DEC/JAN

Geb (1981) and Kays (1982)				Coleman (1982)			
Type	%	$\overline{\theta}_e$ (K)	S	Type	%	$\overline{\theta}_e$ (K)	S
cP	29	282.6-278.8	3.3				
mA	6	282.2-278.5	2.1	I	9.5	282.3	2.8
mP	24	290.4-287.2	2.3	II	43.2	288.5	3.0
cT	5	288.2	?				
cPs	19	292.9-288.2	2.9	III	34.2	295.0	2.9
mPs	8	298.7-294.7	2.7	IV	12.4	302.6	3.8
cA	9	272.5-268.5	large				
mT	1	319.6-315.5	?				

During December and January, cP and mA air which were combined due to similar θ_es occurred much more frequently than the Type I air in Table 10. Also conspicuously absent from the Table 10 data is the extremely cold cA air which accounts for 9 percent of the air masses found by Kays. However, examination of the Dec/Jan graph of the 850mb Berlin data, Fig. 10, shows that an air mass displaying a large standard deviation and $\overline{\theta}_e$ near 272°K is present less than 2 percent of the time.

Frequency histograms for potential temperature and mixing ratio were developed and compared with the works of Davis (1981), McIntyre (1950) and Berggren (1953). These histograms tended to be relatively unimodal, though slightly skewed, when compared to the θ_e distributions. This result agreed with Davis' w and θ frequency histograms over Berlin.

McIntyre and Berggren found two normal distributions using the θ histograms but they could not differentiate between moist and dry air. The θ and w frequency histograms were therefore rejected as candidates for the partial collective technique.

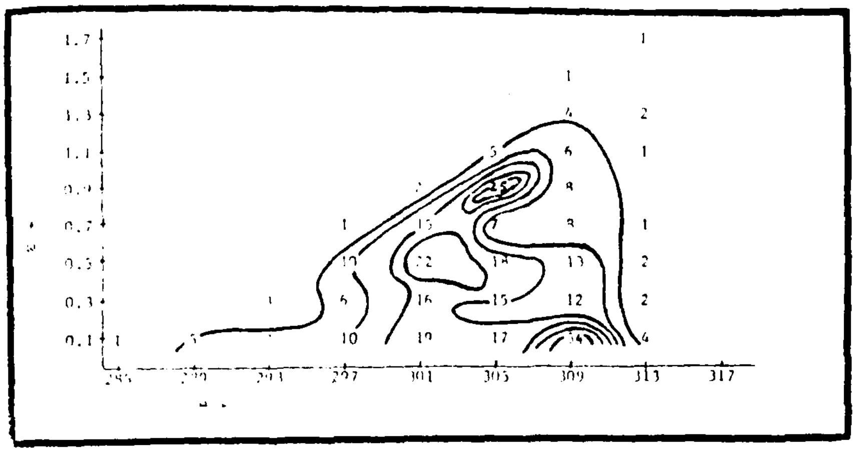

FIGURE 17. θ VS. w FREQUENCY DISTRIBUTION WITH CLUSTERING
(STUTTGART IN WINTER AT 500-mb)

The θ vs. w bivariate distributions for each station and level were also plotted and analyzed as shown above. Some of these graphs display clusters indicating air mass differentiation, Fig. 17, but most of the θ vs. w frequency distributions do not contain recognizable clusters, Fig. 18. These results differ with Davis' but this is probably due to the fact that the manual analyses of the θ vs. w curves accomplished in this study do not subject the data to the maximum likelihood estimators in Wolfe's (1971) NORMIX program.

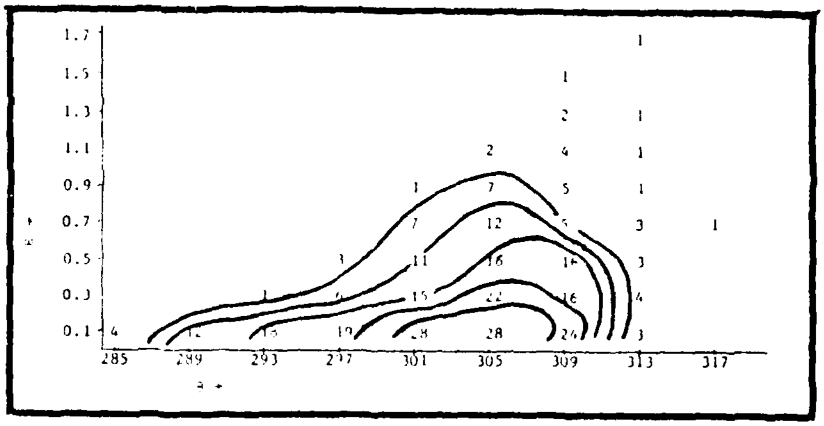

FIGURE 18. θ VS. ω FREQUENCY DISTRIBUTION WITHOUT CLUSTERING (DE BILT IN WINTER AT 500mb)

CONCLUSION

Essenwanger's (1954) partial collective technique provides an adequate means of separating mixtures of normal distributions representing air masses from frequency curves of equivalent potential temperature. This was shown through analysis of the fall and winter θ_e frequency distributions at the surface, 850mb, 700mb, and 500mb levels over six central European stations. Bryson's (1966) simplification of Essenwanger's technique facilitates the application of the partial collective method, but the time involved in manually separating mixed normals is prohibitive. The interactive computer technique developed in this study for separating mixtures of normal distributions enables the researcher to analyze a large volume of data in a reasonable amount of time while maintaining the advantages of the manual method, such as subjective curve by curve inspection to insure reasonable results.

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